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I'late Motion and Crustal Deformation Estimated With Geodetic Data From the Global Positioning System

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Abstract. We usc geodetic data taken over four years with the Global Positioning System (GPS) to estimate (1) motion between six major plates and (2) motion relative to these plates of ten sites in plate boundary zones. The degree of consistency between geodetic velocities and rigid plates requires the (one-dimcasional) standard errors in horizontal velocities to be -2 mm/yr. Each of the 15 angular velocities describing motion between plate pairs that wc estimate with GPS differs insignificantly from the corresponding angular velocity in global plate motion model NUVEL-1 A, which averages motion over the past 3 my. The motion of the Pacific plate relative to both the Eurasian and North American plates is observed to be faster than predicted by NUVEL-1 A, supporting the inference from Very Long Baseline Interferometry (VLBI) that motion of the Pacific plate has sped up over the past few my. The Eurasia-Nor-(h America pole of rotation is estimated to be north of NUVEL-1 A, consistent with the independent hypothesis that the pole has recently migrated northward across northeast Asia to near the Lena River delta. Victoria, which lies above the main thrust at the Cascadia subduction z.one, moves relative to the interior of the overriding plate at 30% of the velocity of the subducting plate, reinforcing the conclusion that tbc thrust there is locked beneath the continental shelf and slope.

Introduction

Geodetic data from VLBI [Ma et al., ,1994] and Satellite Laser Ranging (S1 .R) [Smith et al., 1994] show that plate velocities averaged over the past 15 years nearly equal those averaged over the past 3 my. Velocity variations in the North America-Eurasia-Pacif ic-Australia plate circuit can be no more than ±~20%. Pacific-North America plate motion, however, appears to have been -1 O% faster over the past decade than it has been over the past 3 my. [Ma et al., 1994; Argus and Gordon, ms. in prep., 1995].

In this article wc assess the accuracy of velocities estimated with geodetic measurements made by the International GPS Service for Geodynamics (IGS). Wc estimate the angular velocity between six plates, two more than have been determined with VLB1 and SLR. Wc also estimate the horizontal velocity of ten sites in plate boundary zones, including three near subduction zones with sparse or no data from the other two techniques.

Data Analysis

Jet I'repulsion Laboratory's geodetic anal ysis team estimated the position of 43 sites on 558 days between January 1991 and January 1995. A total of 16348 station-days were analyzed The inversion methods taking observations of range and phase to estimates of position arc described in Heflin et al. [1992] and Blewitt et al. [1992]. The GIPSY/OASIS-11 software was used.

Wc next fit velocities to positions while treating the full variance-covariance matrix using the techniques of Heflin et al. [1994]. The velocities of 12 sites arc based upon data over four years, although for 3 wc solved also for offsets due to the 1992 Landers and 1994 Northridge earthquakes. Twelve velocities arc from data over two years and eight months. The remaining 19 sites have data over no more than two years. The evolution of positions and best-fitting velocities can be examined over the. internet via http;//sidcshow.jpl.nasa.gov/mbh/series.h{n~l.

Sites and Plates

We assigned sites to plates on the basis of geologic and seismologic data, mainly the distribution of major faults and the occu I rence of great and large earthquakes (Table 1). The 9 North Amcricao plate sites provide good geographic coverage of the plate, with the sites at Yellowknife (Northwest Territories), Saint John's (Newfoundland), and Bermuda being in places previously sampled sparsely or not at all. Eight of the 9 Eurasian plate sites lie on the European mainland, with the sole exception being Ny Alesund (Spitsbergen island), which improves the spatial distribution. There are 3 Australian plate sites, 2 in the southeast comer of the continent and 1 on its west side. There arc 2 sites each on the Pacific and African plates. The 2 South American plate sites have data over no more than 2 years.

Table 1. Site to Plate Assignments

North American plate	Eurasian plate
Algonquin Park (Ontario)	Kootwijk (Netherlands)
Yellowknife (Northwest Terr.)	Madrid (Spain)
Saint John's (Newfoundland)	Ny Alesund (Spitsbergen is].)
Westford (Massachusetts)	Tromso (Norway)
North Liberty (Iowa)	Wettzell (Germany)
Bermuda	Onsala (Sweden)
Fort Davis (Texas)	Metsahovi (Finland)
Greenbelt (Maryland)	Herstmonceux (Britain)
Richmond (Florida)	Kiruna (Sweden)
Pacific plate	Australian plate
Kauai (Hawaii)	Yaragadee (Western Australia)
Pamatai (Tahiti)	Canberra (New South Wales)
	Hobart (Tasmania)
African plate	South American plate
Hartebeesthoek (South Africa)	Fortaleza (Brazil)
Maspalomas (Canary isls.)	Kourou (French Guiana)

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Inversion For Plate Velocities

We estimated the angular velocity between the 6 plates while again treating the full variance-covariance matrix. The translation of the velocity origin was determined by minimizing the vertical speeds of the sites on plates. The plate velocities are independent of VLBI, SLR, and NUVEL-1.

Linear propagation of subjective observation errors of 1 meter in range and 1 cm in phase lead to unrealistically tiny velocity uncertainties. The formal standard errors in velocities between sites separated by a few thousand km are tenths of mm/yr. Systematic errors larger than this are evident in seasonal variations in positions. Therefore we added (in quadrature) to each velocity error a systematic error equal to 5 mm divided by the time duration in years over which the site has been observed. This systematic is designed to be precisely large enough to be consistent with the plates being rigid. The 5 mm systematic we add is roughly the same size as the 5.5 mm systematic that Argus and Gordon [ins. submitted to *J. Geophys. Res.*, 1995] add to VLBI velocity errors to satisfy the same criterion. After we add the extra error, the (one-dimensioaal) standard errors in the horizontal speeds between sites a few thousand km apart are typically -1.5 mm/yr for the sites with data over 4 years and -2.0 mm/yr for the sites with data over 2.7 years.

Plate Motion

The angular velocities describing motion between the North American, Eurasian, Pacific, Australian, and African plates are constrained well (Table 2). One component of the angular velocity of the South American plate is not constrained well. There are 15 plate pairs, 10 of which share a plate boundary. No conventional plate motion data (i.e., seafloor spreading rates, transform fault azimuths, earthquake slip vectors) exist along the Pacific-Australia, Australia-Eurasia, Eurasia-Pacific, and North America-South America plate boundaries. The three-dimensional standard error ellipsoids describing uncertainty in the angular velocities have semi-principal axes with lengths between 0.02 and 0.10°/m.y., with the exception of the ellipsoids for the South

Table 2. Angular Velocities Describing Plate Motion

Plate Pair	Angular Velocity Lat. °N	Lon. °E	ω °/m.y.	Pole Error Ellipse σ_{max} °	σ_{min} °	ζ_{max} °	σ_ω °/m.y.
Eurasia-N. Amer.	78.5	122.0	.23	8.2	4.9	-8	.03
N. Amer.-Pacific	49.1	-73.0	.79	4.1	2.2	-83	.03
Africa–N. Amer.	80.9	16.7	.22	14.5	11.1	15	.04
Pacific-Australia	-57.2	-173.5	1.13	2.6	2.4	43	.04
Australia-Eurasia	9.9	47.4	.72	4.9	4.0	--53	.05
Africa–Eurasia	--11.7	-27.3	.07	41.7	36.1	36	.03
Eurasia–Pacific	60.2	-74.4	.95	3.3	2.2	-88	.05
Australia-Africa	11.2	52.6	.71	6.1	4.3	-22	.04
N. Amer.–S. Amer.	6.5	–55.6	.28	8.3	7.4	–55	.12
Africa–S. Amer.	39.9	-49.3	.38	16.2	7.4	-7	.10

The first plate moves counterclockwise relative to the second plate. The uncertainty in pole position is described by the one-sigma error ellipse, which is given by the angular lengths of the semi-principal axes (σ_{max} and σ_{min}) and azimuth of the semi-major axis (ζ_{max}, in degrees clockwise of North). The uncertainty in rotation rate is σ_ω.

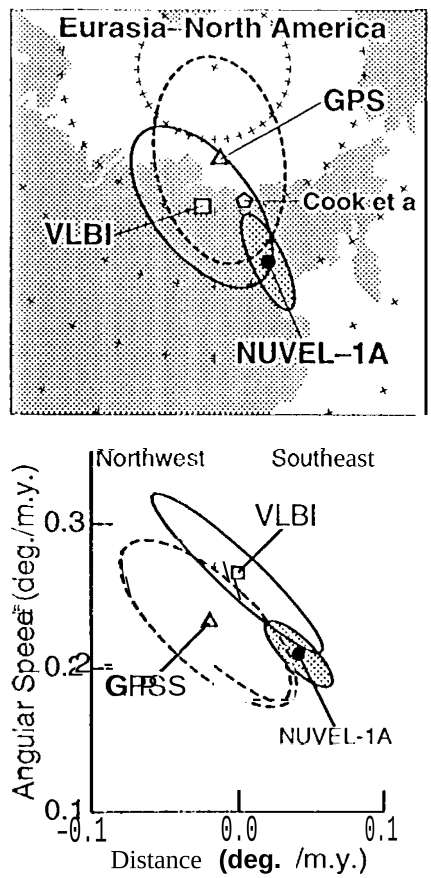

Figure 1. Angular velocities describing Eurasia-North American plate motion and 95% confidence limits. Top: poles of rotation. Bottom: angular velocities in the plane that is both vertical at the location of the VLBI pole and parallel to the long axis of the error ellipse describing uncertainty in that pole.

American plate, which have semi-major axes with lengths of --0.20°/m.y.

Global plate motion model NUVEL-1A [DeMets et al., 1990; 1994], the standard against which we compare, is determine.d mainly from transform fault azimuths and seafloor spreading rates based upon marine magnetic anomalies 3 Ma NUVEL-1 A incorporates recent revisions to the geomagnetic time scale, which result in a 4.4% decrease in all speeds in NUVEL- 1. Each of the 15 angular velocities that we estimate with GPS differs insignificantly from the corresponding angular velocity in NUVEL- 1 A. This means that the three-dimensional 95% confidence ellipsoid describing the summed GPS and NUVEL- 1 A uncertainty includes the vector difference between the two angular velocities. The 95% confidence ellipsoid describing only uncertainty in the GPS angular velocity includes the NUVEL- 1 A angular velocity for 13 of 15 plate pairs, with the 2 exceptions being Eurasia-North America and Eurasia-Pacific.

Argus and Gordon [ins. in prep., 1995] use the VLBI geodetic results of Ma et al. [1994] to determine the 6 angular velocities in the North America-Eurasia-Pacific-Australia plate circuit. Five of the 6 angular velocities differ insignificantly between GPS and VLBI, with the sole exception being Eurasia-North America.

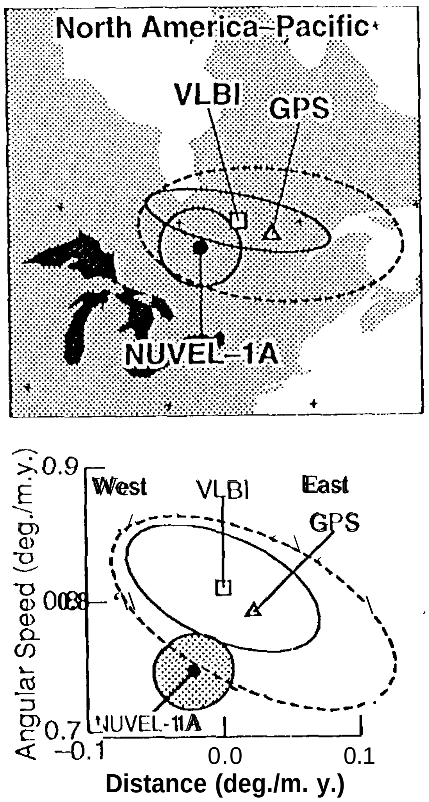

Figure 2. Angular velocities describing North America-Pacific plate motion, Top: poles of rotation. Bottom: angular velocities in the plane that is both vertical at the location of the VLBI pole and parallel to the long axis of the error ellipse describing uncertainty in that pole.

Eurasia–North America Motion

The GPS estimate of the Eurasia-North America pole of rotation lies 15° north of the NUVEL-1A pole (Figure 1). The VLBI pole favors a pole 12° northwest of NUVEL-1A. Therefore the geodetic data support the hypothesis of Cook et al. [1986], which is based mainly upon focal mechanisms in the Chersky mountains, that the pole has recently migrated northward across northeast Asia to near the Lena River delta. Seafloor spreading rates predicted by the GPS angular velocity are slower than those in NUVEL-1A by 1 – 3 mm/yr in the North Atlantic, by 4-5 mm/yr in the Greenland-Norwegian sea, and by 6 mm/yr in the Arctic ocean. The significant difference between the GPS and VLBI angular velocities is evident mainly in angular speed, and is manifested in the GPS angular velocity predicting slower seafloor spreading rates than VLBI.

Pacific–North America Motion

Pacific-North America plate motion appears to have been ~10% faster over the past decade than over the past 3 my. Relative to the North American plate the Hawaiian island of Kauai is observed with VLBI to move at 85 mm/yr toward N48°W [Ryan et al., 1993], which is 10% faster than the NUVEL-1A prediction (77 mm/yr, N45°W). The VLBI angular velocity [Ma et al., 1994; Argus and Gordon, ms. in prep., 1995] has an angular speed a significant 8% faster than NUVEL-1A (Figure 2).

Relative to the North American plate Kauai is observed with GPS to move at 83 ± 3 mm/yr toward N45°W ±2°, which is 2 mm/yr slower than the VLBI velocity and 6 mm/yr faster than the NUVEL-1A prediction. (One-dimensional standard errors are quoted hereinafter.) The GPS angular velocity differs from the VLBI angular velocity by just 0.03 °/m.y, but it differs from NUVEL-1A by 0.06°/m.y. The 95% confidence ellipsoid describing uncertainty in the GPS angular velocity includes most of the VLBI ellipsoid, but excludes about half of the NUVEL-1A ellipsoid. The GPS prediction of the velocity along the straight, narrow segment of the San Andreas fault (at 36°N, 120.6°W) is 53 ±3 mm/yr toward N36°W ±3°, which is 15% faster than the NUVEL-1A prediction (46 mm/yr, N36°W). Therefore the observations suggest that either Pacific-North American plate motion has sped up since 3 Ma, or that some plate motion is taken up outside of the spreading center in the Gulf of California.

Australia-Eurasia Motion

Yaragadee moves relative to the Eurasian plate at 75 ±6 mm/yr toward N20°E ±3°, a velocity nearly equal to the NUVEL-1A prediction (76 mm/yr, N21°E). The GPS and NUVEL-1A angular velocities differ by an insignificant 0.07 °/m.y., though the GPS pole of rotation lies southeast of NUVEL-1A (Figure 3). Because the two VLBI sites on the Australian plate are near each other, the VLBI angular velocity is not constrained well.

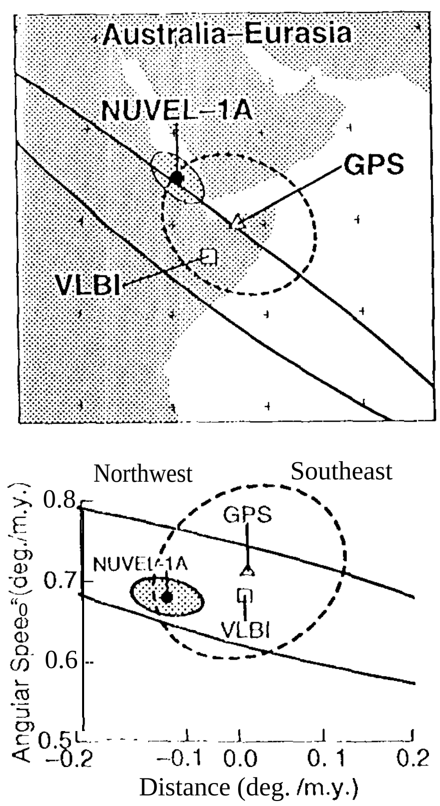

Figure 3. Angular velocities describing Australia-Eurasia plate motion. Top: poles of relation. Bottom: angular velocities in the plane that is both vertical at the location of the VLBI pole and parallel to the long axis of the error ellipse describing uncertainty in that pole.

Table 3. Velocities Between Sites and Plates

Site–Fixed Plate	Lat. °N	Lon. °E	Speed mm/yr	Azimuth °CW of N
Fairbanks–N. Amer.	65.0	-147.5	2 ±2	114 ±54
Penticton–N. Amer.	49.3	-119.6	2 ±2	35 ±50
Victoria–N. Amer.	48.4	–123.5	13 ±2	63 ±10
Matera–Eurasia	40.6	16.7	5 ±2	28 ±23
Graz–Eurasia	47.1	15.5	3 ±3	92 ±52
Quincy–N. Amer	40.0	-120.9	10 ±3	-45 ±19
Harvest–N. Amer	34.5	-120.7	48 ±4	-47 ± 4
Taipai–Eurasia	25.0	121.5	14 ±4	–10 ±14
Usuda–Eurasia	36.1	138.4	33 ±5	–82 ± 8
Santiago–S. Amer.	-33.2	'70.7	18 ±7	88 ±19

Azimuths are in degrees clockwise of North. Uncertainties are one-sigma errors.

Plate Boundary Zone Deformation

The horizontal velocity of 10 sites in plate boundary zones are constrained well (Table 3). The GPS velocity estimates differ insignificantly from corresponding VLBI estimates [Ma et al., 1994; Argus and Gordon, ms. in prep., 1995] for the sites with both kinds of observations (Fairbanks, Penticton, Matera, and Quincy). The motion of Fairbanks and Penticton relative to the North American plate is insignificant, as is the motion of Graz relative to the Eurasian plate. Relative to the Eurasian plate Taipai moves toward the north, in a direction at a high angle to the motion of the subducting Philippine Sea plate. Relative to the South American plate Santiago moves parallel to the subducting Nazca plate, at a fraction of the convergence rate.

Cascadia Subduction Zone Tectonics

Victoria, which lies above the main thrust at the Cascadia subduction zone, moves relative to the interior of the overriding plate in a direction parallel to and at a speed 30% of the velocity of the subducting Juan de Fuca plate (42 mm/yr, N68°E). This observation reinforces the conclusion based upon other geodetic data [Savage et al., 1991; Dragert et al., 1994] that the thrust there is locked beneath the continental shelf and slope. An elastic (edge dislocation) model with locking of the thrust fault over a horizontal distance of 170 km is needed to produce the observed motion, assuming that the thrust dips at 10° from a point 220 km west of Victoria. This estimate of the locked segment is longer than Savage's 135 km. The difference may be due to minor inelastic east-west contraction east of Victoria in the Rocky mountains, which would result in Victoria moving faster toward the plate interior than if elastic strain due to fault locking were the sole cause of its motion.

Conclusion

The GPS velocities are to a high degree accurate, as evident in the their consistency with plate rigidity, and in the close agreement of the GPS angular velocities with NUVEL-1A. GPS is beginning to bring exciting new constraints to the understanding of plate motion and plate boundary zone deformation.

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